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GeoSiphon/GeoFlow Treatment Systems

by

J. E. Cardoso-Neto

Bechtel
Savannah River Site
Aiken, South Carolina 29808

M. A. Phifer
WSRC

F. C. Sappington
WSRC

R. L. Nichols
WSRC

W. N. Ellis
Department of Energy

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GEOSIPHON/GEOFLOW TREATMENT SYSTEMS

M. A. Phifer, F. C. Sappington, R. L. Nichols, Savannah River Technology Center, Westinghouse Savannah River Company; W. N. Ellis, Department of Energy, Environmental Restoration Department; J. E. Cardoso-Neto, Environmental Restoration Division, Bechtel Savannah River Site, Inc.

ABSTRACT

GeoSiphon and GeoFlow Cells (International Patent Application filed December 19, 1997 by WSRC) are innovative alternatives to current groundwater treatment technology. The systems are designed to passively induce contaminated groundwater flow through a permeable treatment media at an accelerated rate by taking advantage of the natural hydraulic head difference between two points. This flow can be produced through the use of siphon (GeoSiphon) or open channel / pressure flow (GeoFlow) between the points of natural head difference without mechanical pumps. The up gradient initiation point is within a contaminated aquifer, and the down gradient discharge point can be to the subsurface, a surface water body, or the ground surface. The permeable treatment media utilized in a GeoSiphon Cell can include materials such as but not limited to granular cast iron, activated carbon, ion exchange materials, limestone, zeolites, iron foam, bimetallics, peat, phosphate rock, dolomite, concrete, fly ash, blast furnace slag, sulfur, pyrite, etc. The permeable treatment media can be applied at the initiation point or the discharge point, it can be applied as in situ or ex situ, and it can be configured to be either permanent or rechargeable.

The world's first GeoSiphon Cell was installed at the Savannah River Site (SRS) TNX facility in July 1997, for the treatment of trichloroethylene and carbon tetrachloride contaminated groundwater. The TNX GeoSiphon Cell is essentially a large 8-foot diameter well, which contains granular cast iron (the treatment media) in place of gravel pack, and passively induces flow by use of a siphon from the cell to an existing outfall ditch. Two phases of testing have been conducted on the TNX GeoSiphon Cell to date. This paper provides a generic overview of the GeoSiphon and GeoFlow technology and an overview of TNX GeoSiphon Cell deployment and demonstration.

GEOSIPHON/GEOFLOW TECHNOLOGY OVERVIEW

GeoSiphon/GeoFlow Configurations

The following three basic GeoSiphon/GeoFlow Cell configurations are described below for illustrative purposes. Multiple other configurations are possible including horizontal well configurations.

- GeoSiphon Cell Pre-Siphon Treatment Cell Configuration (Figure 1)
- GeoSiphon Cell Post-Siphon Treatment Cell Configuration (Figure 2)
- GeoFlow Cell Vertical In-Line Treatment Cell Configuration (Figure 3)

The GeoSiphon Cell Pre-Siphon Treatment Cell Configuration (Figure 1) is an upgradient, large diameter, in situ treatment cell, which contains the permanent permeable treatment media and passively induces flow by use of a siphon from the cell to a surface stream (or ground surface). The siphon flow is induced by the natural hydraulic head difference between the cell and the surface stream (available head). The passively induced flow draws contaminated groundwater through the treatment cell where the permeable treatment media treats the groundwater. The treated water is subsequently discharged through the siphon to the surface stream.

The GeoSiphon Cell Post-Siphon Treatment Cell Configuration (Figure 2) is a recovery well connected by siphon to a downgradient, surface assessable, rechargeable, permeable treatment media cell. The siphon flow is induced by the natural hydraulic head difference between the recovery well and the cell (available head). The passively induced flow draws contaminated groundwater through the recovery well, then through the siphon line, and finally to the treatment cell where the permeable treatment media treats the groundwater. The treated water is subsequently discharged to the ground surface or surface water.

The GeoFlow Cell Vertical In-Line Treatment Cell Configuration (Figure 3) is a large diameter vertical well installed by conventional well drilling techniques, which contains a removable, flow-through, permeable treatment media canister positioned between an upper and lower screen zone. Contaminated groundwater flow is passively induced through the treatment canister due to the head differential between the locations of the upper and lower screen zones. Contaminated groundwater flows into the screen with the higher head, flows through the treatment canister where it is treated, and treated groundwater flows out the screen with the lower head. This can potentially be done within a single aquifer or between aquifers.

A comparison of these GeoSiphon/GeoFlow Cell configurations (Figures 1, 2, and 3) is provided in Table 1. Topography, depth of contamination and other site conditions dictate the configuration most appropriate for implementation.

Table I
GeoSiphon/GeoFlow Cell Configuration Comparison

Comparison Item	GeoSiphon Cell Pre-Siphon Treatment Cell Configuration	GeoSiphon Cell Post-Siphon Treatment Cell Configuration	GeoFlow Cell Vertical In-Line Treatment Cell Configuration
Treatment cell location	Up-gradient of siphon	Down-gradient of siphon	In-line between screen zones
Depth	Limited by maximum 25 foot siphon lift	Limited by maximum 25 foot siphon lift	Only limited by installation equipment limitations
Degassing	Degassing management must be considered for maintenance of siphon. Potential for degassing exists. Treatment may affect quantity and type of degassing	Degassing management must be considered for maintenance of siphon. Potential for degassing typical groundwater dissolved gases such as nitrogen, oxygen, and carbon dioxide exists	Consideration not required from an operational standpoint
Treatment cell influent concentrations	Variable and dependent upon formation contaminant stratification or profile	Averaged formation contaminant concentration; therefore more efficient use of treatment media mass is made	Averaged formation contaminant concentration; therefore more efficient use of treatment media mass is made
Media regeneration or replacement	Acid regeneration possible; media removal and replacement may not be possible	Acid regeneration possible and easy to control; media removal and replacement possible	Removable, flow-through, permeable treatment media canister facilitates media replacement
System head loss	Head loss occurs within the treatment cell, as a well loss, and the siphon line; head loss minimized with this configuration	Head loss occurs within the siphon extraction well or trench, as a well loss, the siphon line, and the treatment cell	Head loss associated with the inlet well screen, treatment media canister, and outlet well screen occurs
Flow considerations	Precipitation induced media porosity loss must be considered	Precipitation induced media porosity loss must be considered	Groundwater geochemical change induce precipitation fouling of the outlet screen must be considered

GeoSiphon/GeoFlow Advantages Over Existing Technologies

The GeoSiphon/GeoFlow Cell is basically an alternative to pump and treat systems, funnel and gate systems, and/or continuous permeable wall treatment systems. Groundwater pump and treat systems consist of recovery wells which extract contaminated groundwater from the subsurface and above grade treatment systems. Due to slow contaminant dissolution and/or migration, groundwater pump and treat systems often require extended treatment periods (i.e. 10s to 100s of years) to reduce the contaminant levels to regulatory standards. These extended periods of operation can require significant energy cost and associated operating and maintenance costs.

In order to overcome the high operating and maintenance costs of pump and treat systems, funnel and gate and continuous permeable wall treatment systems (together labeled as permeable reactive barriers) have been proposed and implemented. Funnel and gate systems consist of impermeable barriers, which funnel the contaminated groundwater through a permeable treatment gate consisting of permeable treatment media. Continuous permeable wall systems consist of a continuous bed of permeable treatment media, which intersects the entire plume perpendicular to the direction of flow. These are passive, in situ systems, which can take significantly longer than pump and treat systems to achieve regulatory clean up standards, since these systems rely only on the natural groundwater flow rates for transport of the contaminants to the permeable treatment media. However these systems achieve remediation with minimal operating and maintenance costs relative to pump and treat.

The GeoSiphon/GeoFlow Cell for the remediation of contaminated groundwater is an innovative and unique alternative to current technologies (pump and treat, funnel and gate, continuous permeable wall). GeoSiphon/GeoFlow Cells have many of the advantages of the current technologies without most of the disadvantages. GeoSiphon/GeoFlow Cells utilize natural hydraulic driving forces to induce accelerated flow rates (greater than natural) for remediation similar to conventional pump and treat systems, but improve upon them through passive operation (no external power requirements), and significantly lower operating and maintenance cost. The passive operation of GeoSiphon/GeoFlow Cells is similar to funnel and gate and continuous permeable wall treatment systems. However, it should incur less initial cost, should cause less land disturbance, uses existing foundation installation and/or well drilling techniques, can induce flow greater than the natural groundwater flow (that is, accelerate clean up), and in some configurations may reduce the potential for pluggage problems, due to mineral precipitation (if discharged to a surface water body, or the ground surface).

TNX GEOSIPHON CELL DEPLOYMENT AND DEMONSTRATION OVERVIEW

TNX Facility Groundwater Contamination Description

The TNX Facility is a semi-works facility for the Savannah River Technology Center (SRTC), which is located a quarter mile from the Savannah River at the Savannah River Site (SRS). TNX is on a terrace above the Savannah River at approximately 150 feet above mean sea level (ft-msl). A portion of the Savannah River flood plain lies immediately west of the TNX Area at 95 to 100 ft-msl. A small levee divides the flood plain and serves as the bank of the river during high stages. Groundwater at TNX can be divided into two main aquifer systems, a shallow and deep aquifer system. The shallow system can be further subdivided into a water table aquifer (35 to 40 feet thick) and a deeper semi-confined aquifer overlain by a clayey silt aquitard. The water table elevation under TNX itself averages 100 ft-msl, under the levee it averages 94 ft-msl, and the Savannah River elevation averages 86. The hydraulic gradients are such that groundwater flows progressively from the deeper aquifers to the shallower aquifers and to the Savannah River. The water table aquifer in the flood plain consists of inter-bedded sand, silty sand, and relatively thin clay layers. Based upon pump tests, estimates based upon sieve analysis, and 3-D modeling the following aquifer parameters have been estimated for the TNX flood plain water table aquifer:

- Horizontal Hydraulic Conductivity ≅ 65 ft/day (2.3E-2 cm/s)
- Vertical Hydraulic Conductivity ≅ 30 ft/day (1.1E-2 cm/s)
- Effective Porosity ≅ 0.15
- Pore Velocity ≅ 3 ft/day (1.1E-3 cm/s)
- Horizontal Gradient ≅ 0.007

Groundwater contamination has been detected at TNX in the water table aquifer (TNX Groundwater RCRA/CERCLA Operable Unit), and consistent with the groundwater flow pattern between aquifers, no contamination has been detected in the semi-confined or deep aquifers. The confirmed contaminants present immediately under the TNX facility itself include trichloroethylene, carbon tetrachloride, tetrachloroethylene, cis-1,2-dichloroethylene, chloroform, 1,1,1-trichloroethane, nitrate, mercury, and gross alpha radioactivity. Elevated chloroform and 1,1,1-trichloroethane concentrations are confined to beneath the TNX facility itself, and these concentrations are not sufficient to significantly impact the groundwater in the TNX flood plain. Additionally the mercury contamination is confined to one well beneath the TNX facility itself, and does not extend into the TNX flood plain. The predominant contaminants detected in the TNX flood plain are trichloroethylene and nitrate; however carbon tetrachloride, tetrachloroethylene, cis-1,2-dichloroethylene, and gross alpha radioactivity may also exist at detectable concentrations within the TNX flood plain.

TNX GeoSiphon Cell Deployment and Description

The TNX GeoSiphon Cell (TGSC-1) was built with a Pre-Siphon Treatment Cell Configuration (see Figure 1). TGSC-1 is essentially a large 8-foot diameter well, which contains granular cast iron (the treatment media) in place of gravel pack. It was installed utilizing an auger and removable caisson within the TNX flood plain from July 7, 1997 to July 17, 1997. Figure 4 provides the as-built conditions of TGSC-1. The cell consists of the following major components with the functions as listed:

- A geonet with a geotextile bonded to both sides has been placed between the soil and the granular cast iron. This geonet with geotextile performs the following functions:
  - The geotextile acts as a filter preventing migration of soil particles into the granular cast iron and preventing pluggage of the geonet.
  - The geonet has a high planar transmissivity. This high planar transmissivity, which is vertically oriented, should provide a more even distribution of head and flow with depth and subsequently a more even distribution of the contaminants over the granular cast iron cylinder surface area than exists within the formation itself. This should minimize short-circuiting of elevated formation contaminant layers through the granular cast iron.
- A steel plate and a high density polyethylene (HDPE) membrane has been placed below and above the granular cast iron, respectively, to promote horizontal flow through the granular cast iron and prevent short circuiting of the contaminated groundwater.
- A 12-inch diameter screen and casing has been placed in the center of the granular cast iron cylinder to allow insertion of the siphon line and withdrawal of the treated groundwater.
- The granular cast iron treats the chlorinated volatile organic compounds (CVOCs) by the process of zero valent iron enhanced abiotic degradation. Due to the geometry of the GeoSiphon Cell, flow through the iron is horizontal, radially inward flow with an increasing velocity from the geonet with geotextile exterior to the 12 inch diameter screen interior. Approximately 49.7 tons of 0.25 to 2.0 mm (particle size) granular cast iron have been utilized in TGSC-1. The as-built granular cast iron porosity is 0.68. The as-built granular cast iron treatment zone extends from a radius of 0.53 to 4.0 feet.
- The bentonite seal and lean fill has been placed to prevent surface infiltration into the GeoSiphon Cell and to bring the cell to grade.
- 9 ¼ inch stainless Steel sampling ports allow collection of samples along one horizontal, radial flow path.

Contaminated groundwater flow through the granular cast iron in the treatment cell is passively induced by use of a siphon from the cell to the existing X-08 outfall ditch. The flow is induced by the natural hydraulic head difference between the cell and the outfall ditch. The granular cast iron treats the CVOCs by the process of zero valent iron enhanced abiotic degradation. The treated water is subsequently discharged through the X-19 outfall to the X-08 outfall ditch, which flows into the Savannah River.

Zero valent iron enhanced abiotic degradation of CVOCs is essentially a reductive dechlorination process, which uses granular cast iron as the reducing agent, and produces final reaction products such as methane, ethane, ethene, and chloride ions in the degradation of trichloroethylene. During this treatment process, the Eh (oxidation/reduction potential) decreases (that is, reducing conditions are produced) and the pH increases. This treatment media has been developed and patented by the University of Waterloo and is marketed by EnviroMetal Technologies, Inc. All that is required for treatment of CVOC contaminated groundwater using this technology is to provide sufficient contact time between the contaminated groundwater and the granular cast iron. The CVOC reduction appears to be a surface activated reaction, which may require the adsorption of the CVOCs onto specific active surface sites on the iron. Two competing degradation pathways appear to exist:

- Step-wise dechlorination pathway
- Multiple dechlorination pathway

Following the step-wise dechlorination pathway, the iron is oxidized, water dissociates to form hydrogen ions and gas, and the chlorine on the CVOCs are replaced with hydrogen (CVOCs reduced) in a step-wise fashion. In this pathway trichloroethylene degrades to cis-1,2-dichloroethylene, cis-1,2-dichloroethylene in turn degrades to vinyl chloride, and vinyl chloride subsequently degrades to methane, ethene, and ethane. Following the multiple dechlorination pathway, the iron is oxidized, trichloroethylene degrades to chloroacetylene with the removal of two chlorines (reduced), chloroacetylene degrades to acetylene with the removal of one chlorine (reduced), and acetylene finally degrades to methane, ethene, and ethane. (1, 2, 3, 4)

TNX GeoSiphon Cell Testing

Two phases of testing have been conducted on the TNX GeoSiphon Cell (TGSC-1) to date. Phase I testing consisted of pumped flow to the TNX National Pollutant Discharge Elimination System (NPDES) X-08 outfall from the treatment cell, so that steady state flow conditions could be created. Creation of steady state conditions facilitated the determination of field first order rate constants (k) and the determination of the maximum acceptable treatment flow rate. Phase II testing consisted of siphon flow establishment between the treatment cell and the existing X-08 outfall ditch. This phase focused upon application of siphon technology as a sub-component of the overall GeoSiphon Cell technology. Siphon flow, design, installation, and operating parameters were evaluated.

Phase I testing began on August 5, 1997 and was completed on December 16, 1997. During Phase I steady state conditions were created, so that field first order rate constants (k) for the CVOCs and the associated maximum acceptable treatment flow rate (i.e. flow rate that allows reduction to below Primary Drinking Water Standard Maximum Contaminant Levels (PDWS-MCLs)) could be determined. In order to determine k, groundwater contaminant degradation through the granular cast iron was monitored along one horizontal, radial flow path using a series of stainless steel sampling tube locations (see Figure 4). In order to determine reduction to below the MCLs, discharge concentrations were determined from a sampling port on the discharge line and from the end of the discharge line at the NPDES X-08 outfall.

The following Phase I flow rates through TGSC-1 were utilized:

- 1 gpm from August 5 to September 30, 1997
- 4 gpm from September 30 to November 11, 1997
- 8 gpm beginning on November 11 to December 16, 1997

Results from Phase I testing indicate that the degradation of trichloroethylene, itself, is the limiting compound to treatment below the PDWS-MCLs within the TNX GeoSiphon Cell. Figure 5 provides the steady state trichloroethylene degradation profiles through the treatment cell for each of the flow rates utilized. Little, if any, cis-1,2-dichloroethylene and trichloromethane (chloroform) as trichloroethylene and carbon tetrachloride intermediate degradation products, respectively, were produced during Phase I testing. Additionally no vinyl chloride was detected during Phase I testing. Based upon this lack of cis-1,2-dichloroethylene, vinyl chloride, and chloroform intermediate degradation product production, it appears that degradation within TGSC-1 is predominately following the multiple dechlorination pathway (chloroacetylene/acetylene) as discussed above. The average trichloroethylene first order rate constants (k) produced from the steady state trichloroethylene data (see Figure 5) increased with increasing flow rate as shown in Table II. This degradation within TGSC-1 resulted in a maximum acceptable treatment flow rate of between 7.8 gpm and 8.3 gpm. At this flow rate greater than 200 μg/l trichloroethylene contaminated groundwater at could be treated within the TNX GeoSiphon Cell (TGSC-1) while maintaining the average discharge TCE concentration below 5 μg/l. Figure 6 provides a plot of the flow rate versus the trichloroethylene discharge concentration.

Table II
Trichloroethylene First Order Rate Constants (k)

Flow Rate (gpm)	First Order Rate Constant, k (1/hr)	Half-life, $t_{½}$ (hrs)
0.97	0.347	2.0
4.00	0.578	1.2
7.98	0.917	0.76

Testing of four different siphon line configurations was conducted during Phase II testing from June 18, 1998 to September 4, 1998, and a one-day minimum flushing velocity test was conducted on November 13, 1998. A siphon is a closed conduit which passively (i.e., no power input) conveys liquid from a point of higher hydraulic head to one of lower head after raising it to a higher intermediate elevation which is at sub-atmospheric conditions (negative pressures). In other words a siphon is essentially a passive vacuum pump. A siphon has a maximum theoretical lift of 34 feet (equivalent to atmospheric pressure); however it has a maximum practical lift of 25 feet due to the vapor pressure of water and friction head loss.

Siphons require priming (initial filling of line) to initiate flow. After priming, the siphon will passively convey liquid from the point of higher hydraulic head to the one of lower head indefinitely so long as the head differential is maintained and the prime is not lost. (5, 6, 7, 8)

Accumulation of air can break the siphon, however this can be avoided by employing the following (5, 6, 7, 8):

- Use of submerged inlets and outlets to prevent air from being drawn into the siphon line
- Maintenance of full flow in the siphon line through the removal of gases from the siphon line, which degas within the siphon line due to the sub-atmospheric pressures. One or both of the following methods may be utilized to maintain full siphon flow:

  – Maintenance of the minimum flushing velocity required to transport gases, which have degassed from the liquid, out the end of the siphon
  – Use of air chambers at the siphon crest to remove gases, which have degassed from the liquid, from the siphon

Within all the tests, the management of gas within the siphon line was determined to be of utmost important in maintenance of siphon flow. Siphon line gas management requires control of gas bubble transport, accumulation, and agglomeration and elimination of gas bubble entrapment. Gas bubble transport, accumulation, agglomeration, and entrapment are controlled by fluid flow velocity, gas buoyancy, and siphon line grades and inside diameter discontinuities (i.e. fittings). Gas bubble transport in the upward leg of the siphon line is facilitated by higher fluid flow velocities, a continuous upward siphon line grade (no localized high points), and the minimization or elimination of fittings, which produce discontinuities in the inside diameter of the siphon line. The continuous upward grade and elimination of such fittings promotes buoyancy transport in the same direction as fluid flow and eliminates the accumulation, agglomeration, and entrapment of gas bubbles in the upward leg of the siphon line. The fluid flow velocity in the upward leg is not as critical as it is in the downward leg of the siphon line, and the upward leg fluid flow velocity should be balanced against minimization of head loss to maximize overall flow rates.

The direction of gas bubble transport, if any, in the siphon line downward leg is determined by whether transport due to fluid flow velocity or gas buoyancy is dominant. Fluid flow velocity tends to cause the gas bubbles to move downward in the downward leg of the siphon line toward the end of the line. Gas buoyancy tends to cause the gas bubbles to move upward in the downward leg of the siphon line toward the siphon crest.

In order to utilize the minimum flushing velocity to maintain full flow in the siphon line downward leg, the fluid flow velocity must be dominant in the downward leg. That is the fluid flow velocity must be greater than the required minimum. Additionally a continuous, downward, siphon line, grade (i.e. no localized high points) and the minimization or elimination of fittings, which produce discontinuities in the inside diameter of the siphon line, is necessary. The continuous downward grade and elimination of such fittings eliminates the accumulation, agglomeration, and entrapment of gas bubbles in the downward leg of the siphon line.

In order to utilize an air chamber to maintain full flow in the siphon line downward leg, the gas buoyancy must be dominant in the downward leg. That is the fluid flow velocity must be less than the minimum, and the downward slope of the siphon line must be continuous (i.e. no localized high points) and steep enough for gas buoyancy to overcome the fluid flow velocity. This allows gas transport up the downward leg to the crest, where the air chamber is located. Additionally fittings, which could entrap gas bubbles, should be minimized. The continuous downward grade and minimization of such fittings eliminates the accumulation, agglomeration, and entrapment of gas bubbles in the downward leg of the siphon line.

The optimized Phase II siphon line configuration tested utilized an air chamber to maintain full flow in the siphon line. It consisted of 305 feet of 1-½ inch pipe on a consistent engineered slope, with both the up-gradient (at 1:100 slope) and down-gradient legs (at ~22-½° slope) from the air chamber sloping upward toward the air chamber (see Figure 7). An initial head differential of approximately 1.43 feet between the cell and the X-08 outfall ditch resulted in an initial recorded flow rate of 2.71 gpm. A flow rate of 2.69 gpm was calculated, based upon these initial conditions. The siphon operated continuously over a greater than 6 day period at flow rates varying from 2.23 to 3.98 gpm, with an average flow rate of 2.62 gpm (see Figure 8). Operation of this siphon line configuration resulted in continuous, consistent operation with flow rates consistent with calculated values. Re-priming was not required, however water recharging of the 7-½ gallon air chamber was required on a 23 to 25 hour basis. The air chamber can be sized to minimize the frequency of required water recharging. This siphon line configuration with air chamber was able to maintain full siphon line flow by removal of gas bubbles from in its entire 305-foot length.

Based upon the results of the Phase II testing, a new siphon line will be installed capable of matching the maximum acceptable treatment flow rate of the treatment cell (approximately 8 gpm). A 200-gallon air chamber will be provided to lengthen the period of time required between air chamber recharging events. The end of the new siphon line will be installed within the X-08 outfall ditch in a location that provides approximately 5 feet of head differential to drive the system (significantly more head differential than provided by the previously tested installation). It has been calculated that this head differential will be capable of producing approximately 9.5 gpm of flow through TGSC-1.

CONCLUSIONS

GeoSiphon and GeoFlow Cells (International Patent Application filed December 19, 1997 by WSRC) are innovative alternative to current groundwater treatment technology. They have many of the advantages of the current technologies without most of the disadvantages. They can minimize the operating and maintenance costs associated with pump and treat systems, and they potentially accelerate clean up as compared to funnel and gate and continuous permeable wall treatment systems.

The world's first GeoSiphon Cell was installed at the Savannah River Site (SRS) TNX facility in July 1997, for the treatment of trichloroethylene and carbon tetrachloride contaminated groundwater. The Phase I testing indicated that a maximum acceptable treatment flow rate of approximately 8 gpm of groundwater contaminated with greater than 200 μg/l trichloroethylene could be treated within the TNX GeoSiphon Cell (TGSC-1), while maintaining the average discharge trichloroethylene concentration below 5 μg/l. The Phase II testing indicated that the siphon could maintain continuous, consistent operation with flow rates matching the maximum acceptable treatment flow rate of the treatment cell (approximately 8 gpm).

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Figure 1
GeoSiphon Cell
(Pre-Siphon Treatment Cell Configuration)

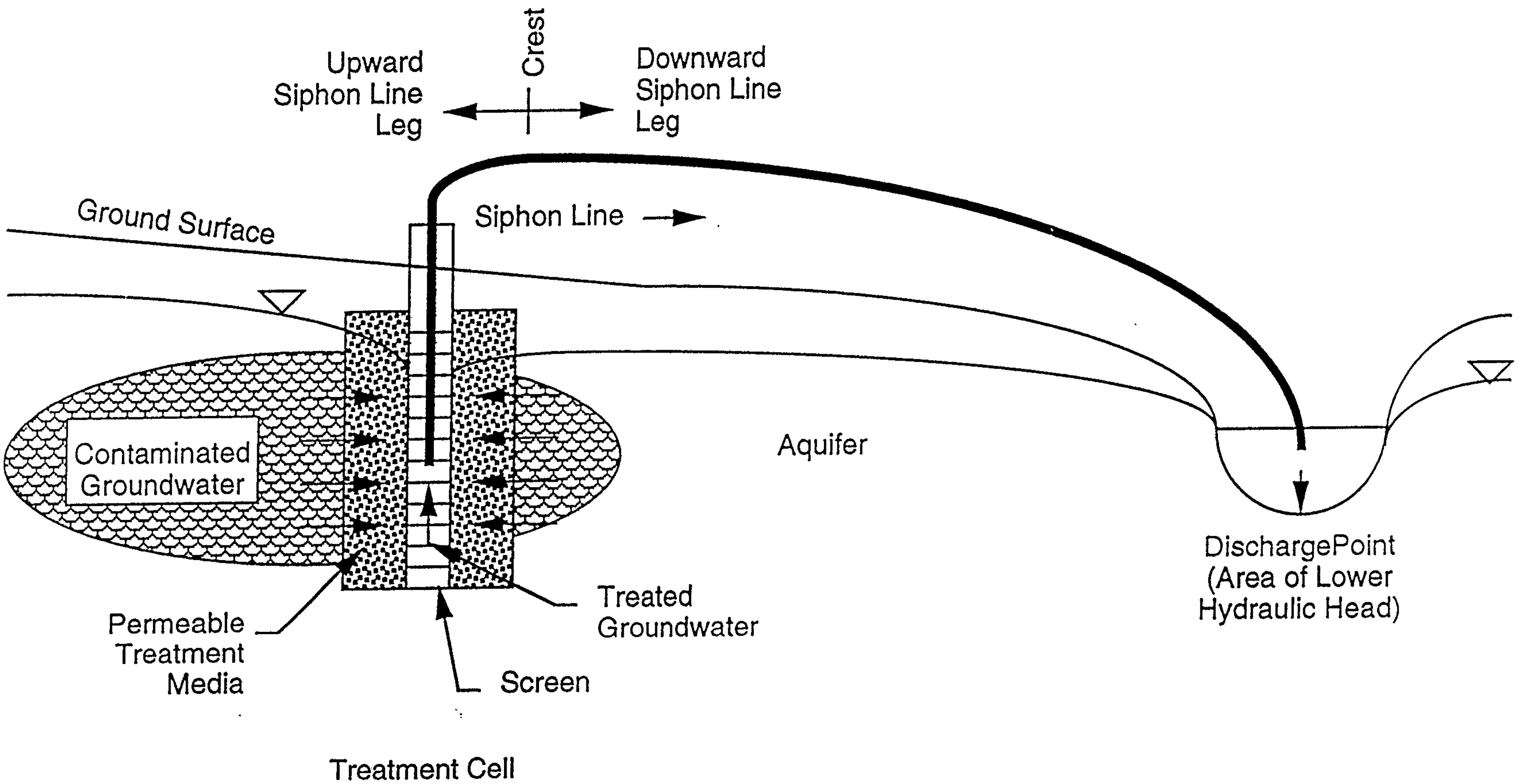


Figure 2
GeoSiphon Cell
(Post-Siphon Treatment Cell Configuration)

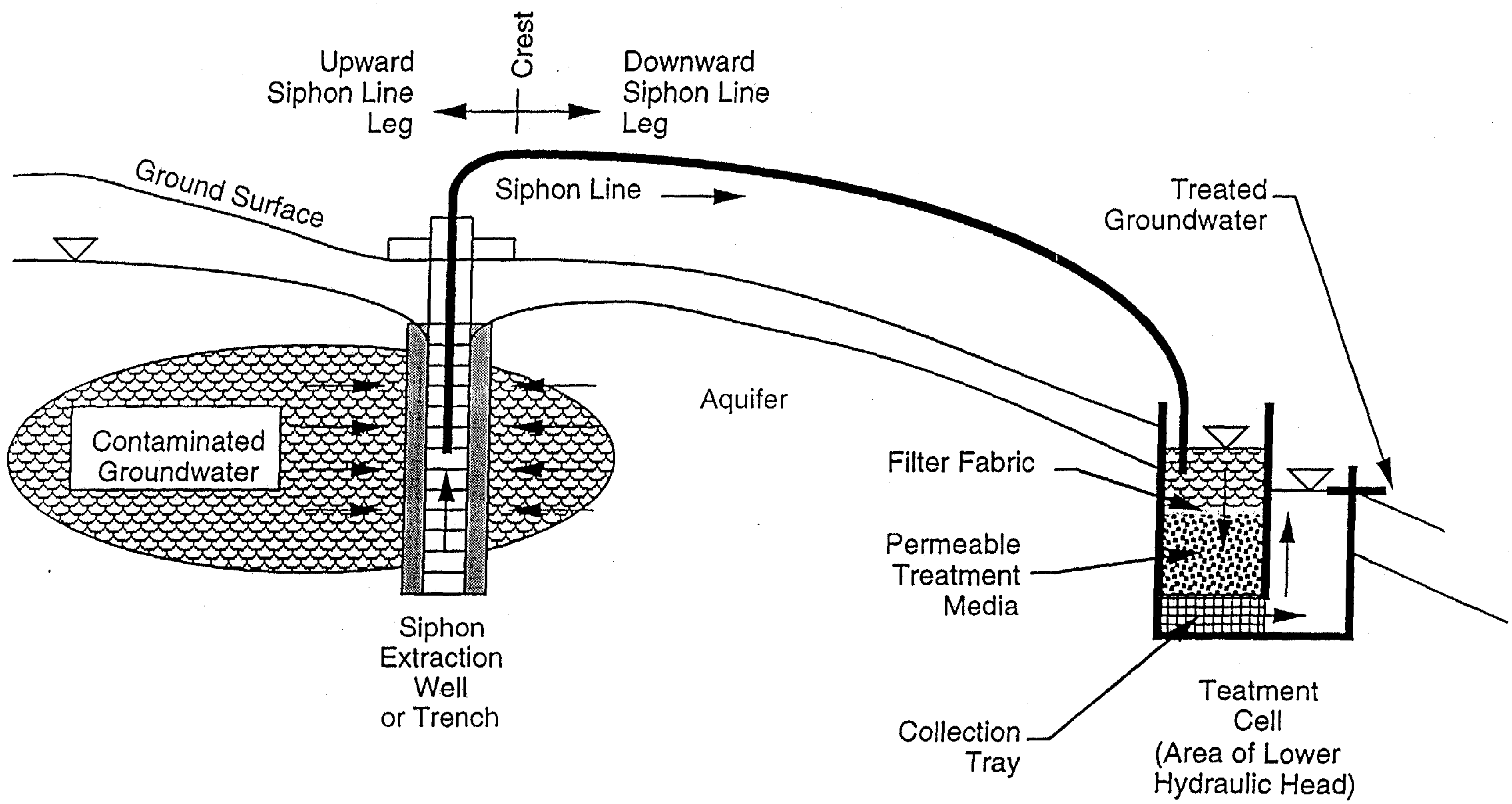


Figure 3
GeoFlow Cell
(Vertical In-Line Treatment Cell Configuration)

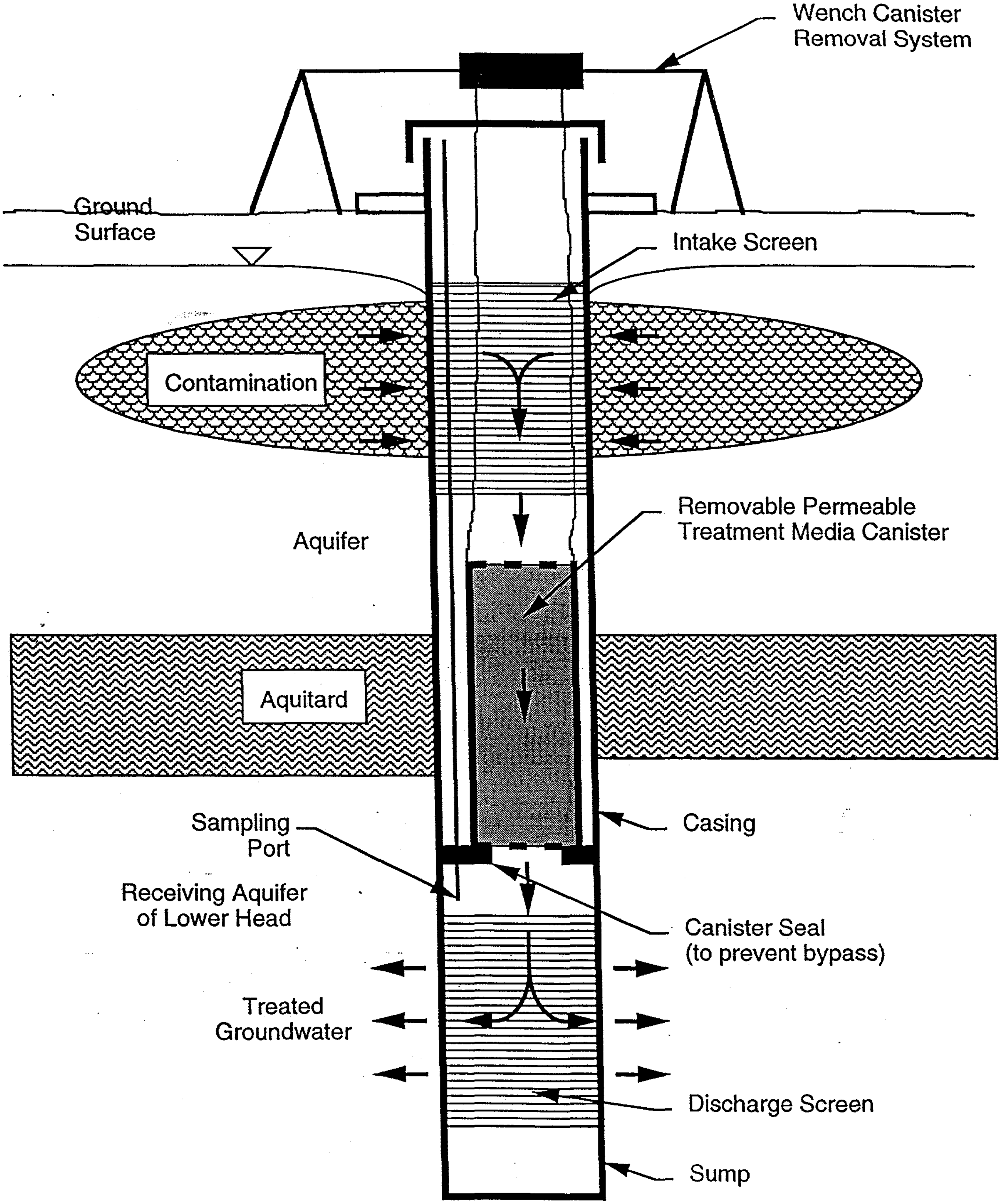
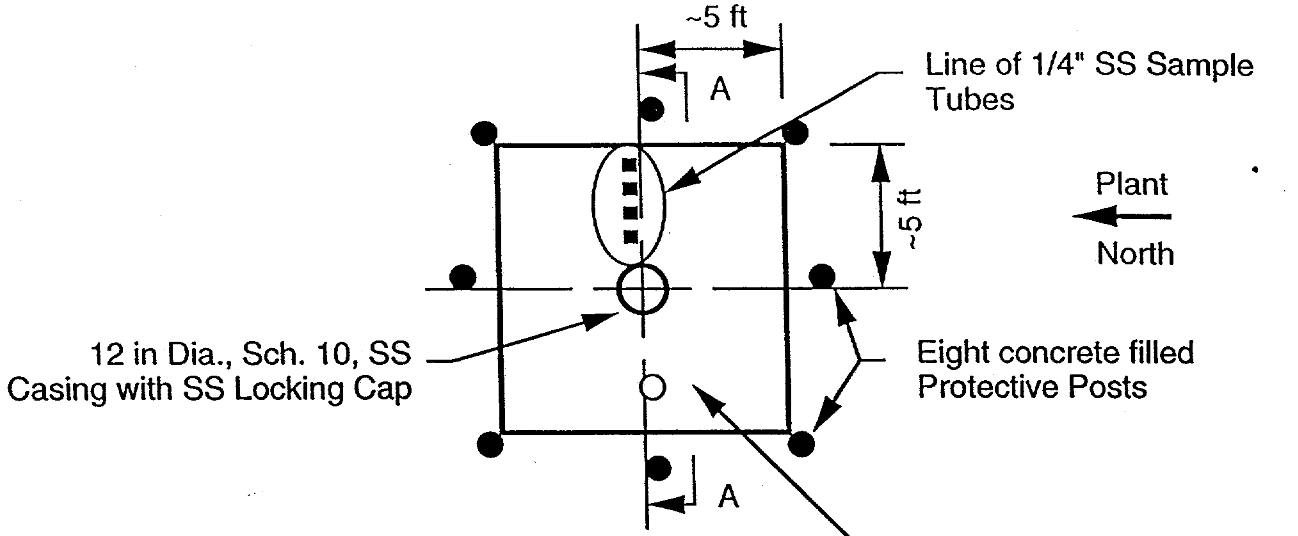
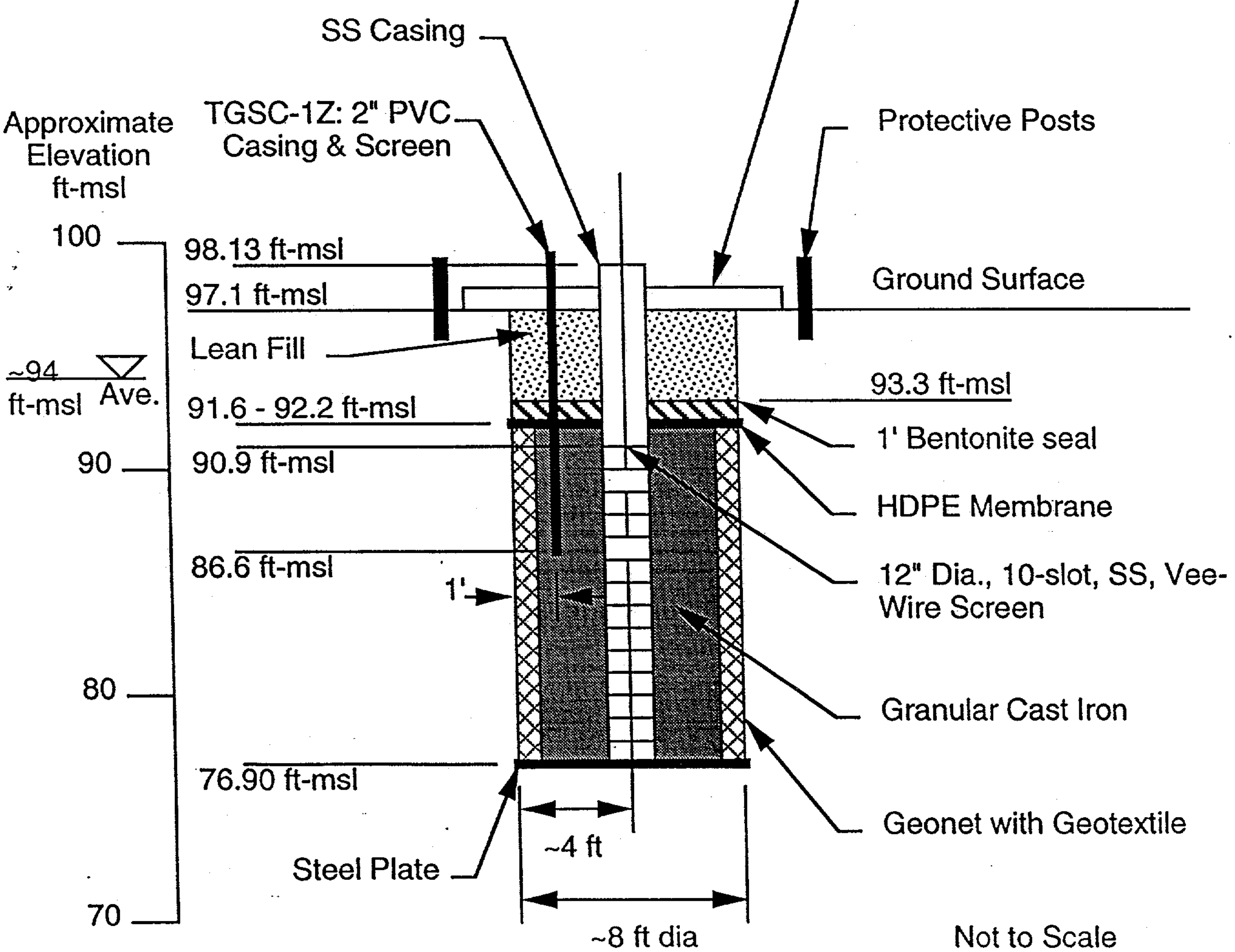


Figure 4
TNX GeoSiphon Cell (TGSC-1)



Plan View



Section A-A

Figure 5
TCE Degradation
TGSC-1 Steady State Profiles

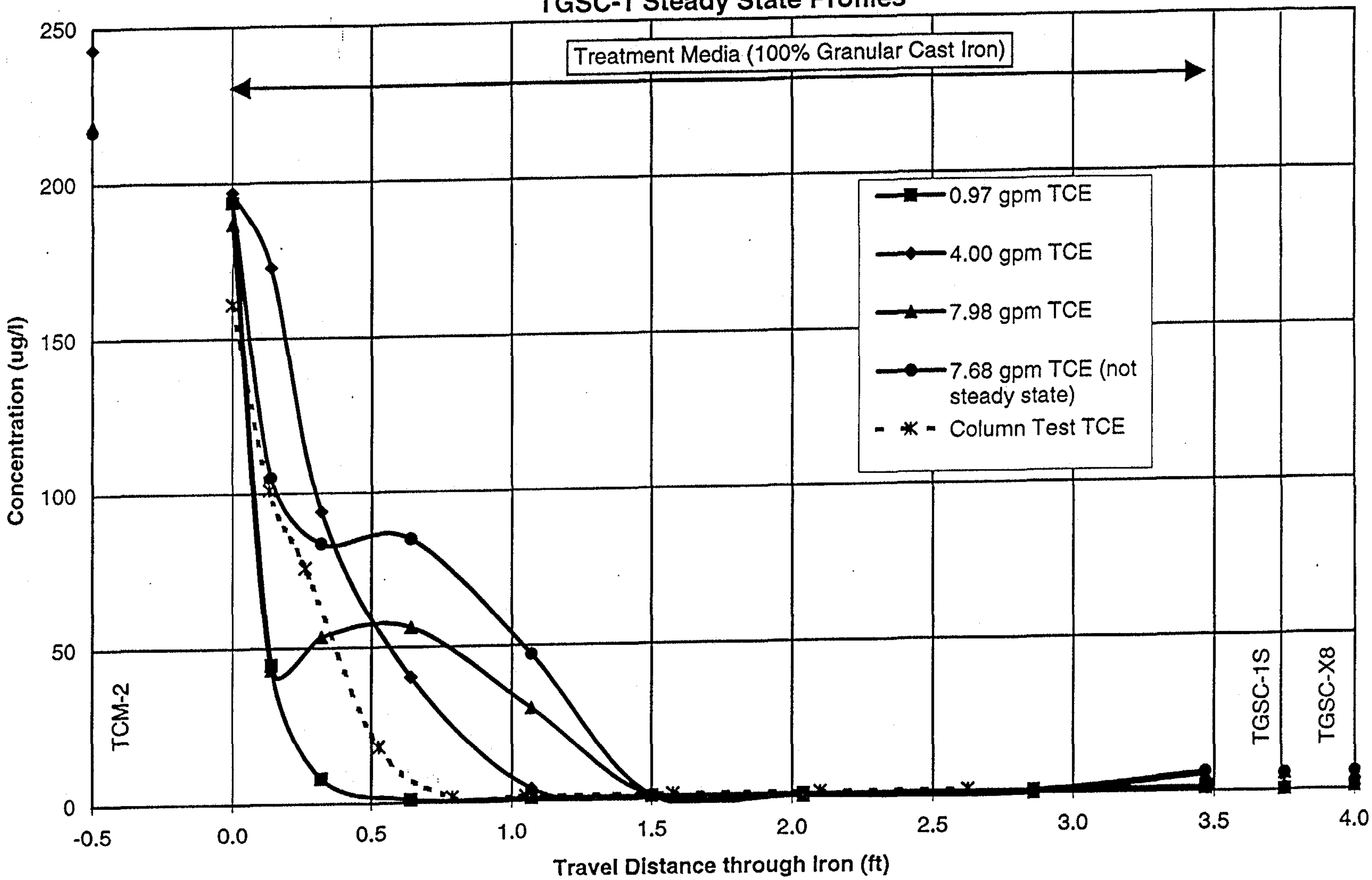


Figure 6
Flow Rate Versus TCE Discharge Concentration

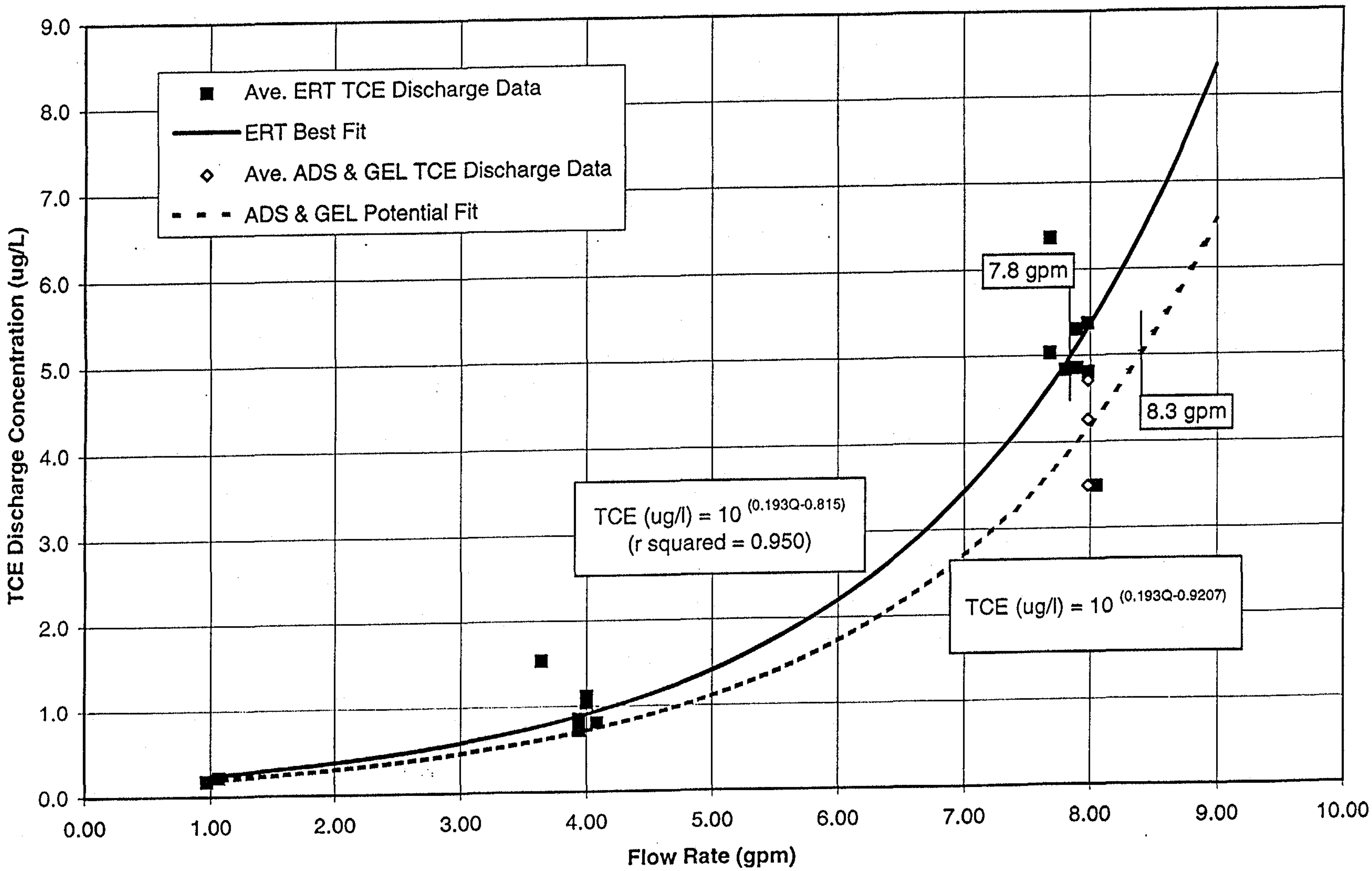


Figure 7
TGSC-1 Siphon Line Profile

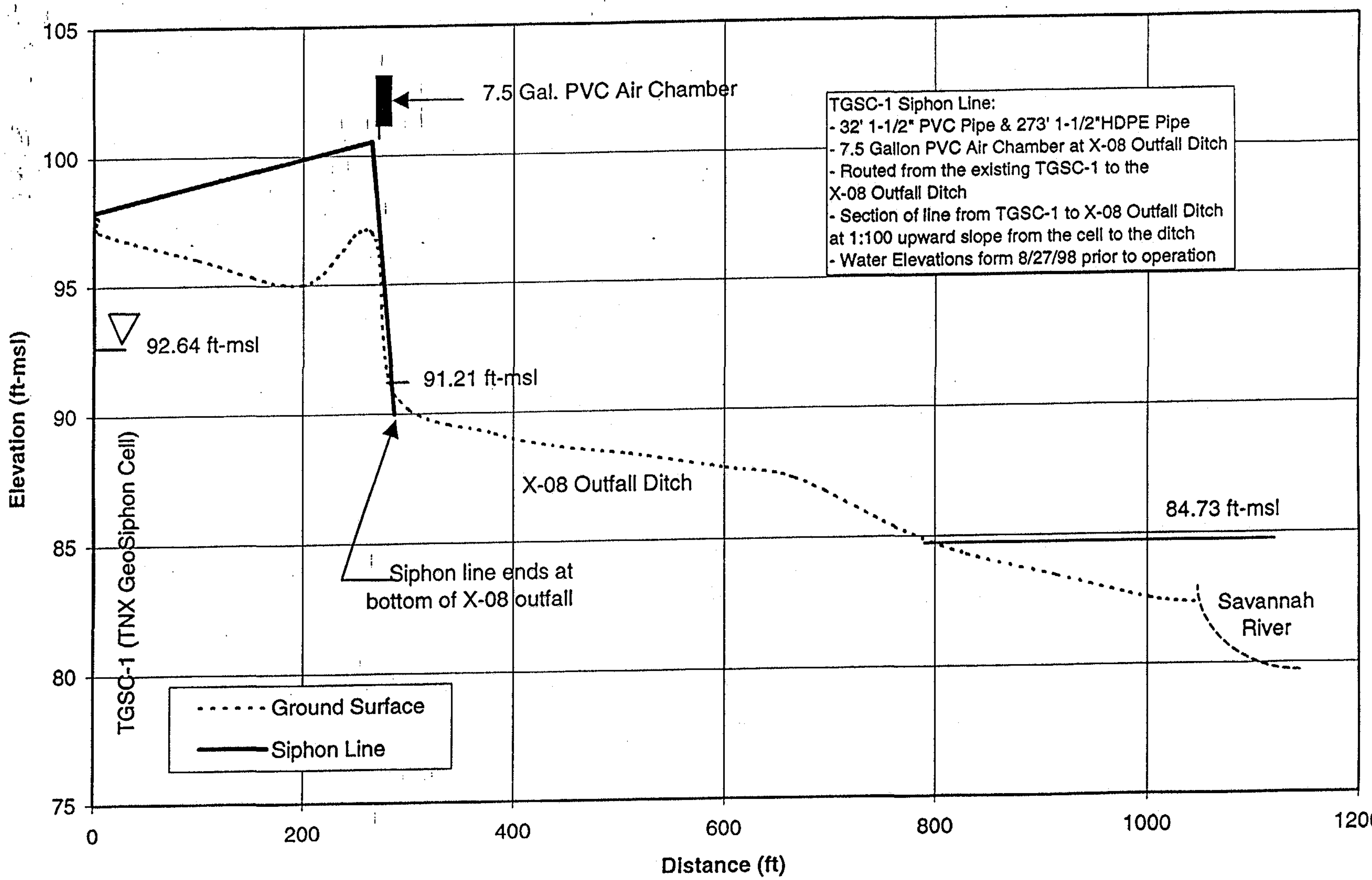


Figure 8
TGSC-1 Phase II Flows and Water Elevations